Monitoring landslide movement and triggering factors in near real-time – an example from Taihape, New Zealand

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ABSTRACT
A novel technique has been deployed to monitor a landslide in Taihape, New Zealand. The landslide covers approximately 45 hectares and contains over 200 households, including a primary school. The initial landslide is thought to be between 1,800 and 11,000 years old. Evidence from movement monitoring over the past 20 years indicates that parts of the landslide have been episodically active and recent prolonged rainfall has caused the landslide to accelerate, resulting in significant damage to services, roads and homes. Because of this recent accelerated movement, a near-real time monitoring system has been installed on the landslide.

The project involves a combination of field mapping, sub-surface investigation and near-real time monitoring of rainfall, ground-shaking intensity, groundwater levels and surface movement. The data from the landslide are being used to correlate different rates of surface movement to the triggering factors enabling triggering thresholds to be established. Until this year, monitoring had been carried out manually, with the monitoring frequency ranging from once a year to once every five years. A key component is a laser survey network that automatically tracks, at defined (hourly) intervals, the positions of reflectors placed on the landslide. The movement data, along with data from piezometers, rain gauges and strong-motion accelerograph installed on the landslide are transmitted by radio and internet to GNS Science, and can be viewed in near real-time via the web. The greater temporal and spatial resolution of the monitoring network is allowing movement triggering intensity/duration thresholds to be developed, which in the future will allow alert levels to be set once a better understanding of the landslide movement pattern has been established. The capability being developed with this project has the potential to be applied to other deep-seated landslides, and is providing new insights into the movement patterns of these types of landslide.

1 INTRODUCTION

The monitoring of landslides is typically done for two reasons: to investigate and assess landslide movement patterns for mitigation purposes; and to provide some form of warning system. The investigation and interpretation of landslide movement patterns have been undertaken using a wide range of techniques, including the use of survey marks; extensometers; inclinometers; analogue and digital photogrammetry, both terrestrial and aerial; synthetic aperture radar interferometry (InSAR) (Petley. et al., 2004) and more recently LiDAR surveys, both terrestrial and aerial. Rainfall intensity-duration thresholds, in combination with rainfall forecasts and real-time rainfall measurements have been the basis for operational landslide warning systems in several areas of the world including Hong Kong (Chan. et al, 2003), America (Keefer. et al, 1987) and England (Cole and Davis, 2002). These systems are operated over broad regions or in specific areas where people and infrastructure are at risk from landslides (NOAA-USGS, 2005). Although new movement monitoring techniques have improved the understanding of landslide movement patterns in recent years, these techniques suffer from serious shortcomings in terms of spatial or temporal resolution (Petley. et al., 2004) and as a result many monitoring programmes are not able to link specific periods of landslide movement to the factor that triggered the movement. Other shortcomings in landslide monitoring, especially for landslide warning systems, are the ways in which the monitoring data are collected, transferred, processed, and ultimately displayed. Solutions to these problems have been implemented at the Taihape landslide. This paper discusses key aspects of the installed monitoring equipment; transfer, processing and display of the monitoring data; as well as presenting results from the first six months monitoring, which are already providing new insights into the movement patterns of this complex landslide.

2 THE TAIHAPE LANDSLIDE

2.1 Landslide setting

The Taihape landslide is located in Taihape township, central North Island, New Zealand (Figure 1). It consists of a large, deep-seated, translational slide that has developed in Tertiary-age sandstones. It is estimated to have originated between 1,800 to 11,000 years ago (Thompson 1982) and is presently active. The area of land within the landslide is approximately 45 hectares (Tonkin & Taylor, 2006), including 209 households, 388 residents and a primary school. The Tertiary rocks of central North Island, New Zealand, are prone to large landslides, a number of which are located in the Taihape area. The occurrence of the landslide is closely related to the regional geological setting. East west compression and relatively rapid uplift has lead to gentle folding of the Tertiary rocks (Thompson, 1982). As a result the Taihape Sandstone has a regional dip of approximately 7° towards the south-southeast (Thompson, 1982). The Taihape area is also traversed by a series of north-northeast to south-southwest striking faults, including the Taihape fault, which forms the western flank of the landslide. The fault is classified as 'active' (defined as faults that have moved in the last c.125,000 years, and are likely to move again in the foreseeable future causing a large earthquake (~>/= M7) and ground-surface rupture) and a prehistoric earthquake on this fault could be associated with the development of the initial failure. The landslide slip plane has been identified from various ground investigations and ranges from 22m below ground level in the toe of the landslide to 34m near the back scarp of the landslide, and comprises a thin (5 to 10mm) layer of slickensided clay material (Tonkin & Taylor, 2006), thought to represent bedding-plane shear, as the historical direction of landslide movement (bearing 160°) is coincident with the regional dip direction of bedding (Thompson, 1982).

Figure 1: Map showing the location of Taihape.

2.2 Landslide background

Due to the size, location and recent activity, the Taihape landslide has been studied for scientific and property insurance purposes since 1971, when significant ground deformation was first noticed. Monitoring began in 1984 with the installation of 2 standpipe piezometers and 3 inclinometers. A ground deformation network was established in 1985 comprising 25 survey marks. Routine monitoring of the deformation network in 2004 identified that the movement rate of the landslide had increased significantly and signs of surface deformation had started to appear in the infrastructure around the landslide toe. As a result, an additional 5 inclinometers and standpipe piezometers were installed in 2005/2006 (Tonkin & Taylor, 2006). Although some good quality historical monitoring data are available for this landslide, the temporal resolution of this information are poor, as the data from the equipment was downloaded and processed manually, at sporadic intervals. The measurement frequency of the surface deformation network has varied from 6 months to 5 years; the 2005/2006 inclinometers are currently measured every two weeks and the standpipe piezometers also measured every two weeks but increased to daily measurements during periods of wet weather. More recently the inclinometers have been used to determine landslide movement (Williams. et al., 2007), however, the spatial resolution of these is limited to a line through the landslide and so it is not possible to determine movement patterns from these data alone.

The monitoring data have been compared to rainfall, and more recently earthquake records to link landslide movement to potential triggering events. Making these links has been difficult due to the lack of site-specific rainfall and ground acceleration data and the poor temporal resolution in the movement monitoring data. Monitoring equipment operating in a near-real time framework has been installed on the landslide to both increase the spatial and temporal resolution of the monitoring, and to record movement triggering events, therefore allowing discrete periods of landslide movement to be better linked to the triggering event.

3 THE MONITORING NETWORK

3.1 Equipment

Equipment has been installed to monitor two triggering factors, rainfall and ground-shaking intensity; and two response factors, ground-water levels and surface movement. A key component is the movement-monitoring system, which utilises reflectors (currently 30 prisms) located across the landslide to provide a high level of spatial resolution (Figure 2). High temporal resolutions are achieved through a robotic total-survey station that seeks and measures the location of each reflector at hourly intervals (Figure 3). The positions of the reflectors are based on engineering geological mapping of the landslide features (at a scale of better than 1:1000) and a review of the historical monitoring data, with reflectors staggered across pertinent geomorphological features (Figure 4). Rainfall is recorded by two tipping-bucket rain gauges located on the toe and near the back scarp of the landslide (Figure 4), and groundwater levels are recorded at five-minute intervals using 4 vibrating wire piezometers installed in 4 boreholes across the landslide (Figure 4). The piezometers have been installed to monitor groundwater acting along the slip plane of the landslide. In addition to movement triggered by rainfall, and due to the proximity of the landslide to the active Taupo Volcanic Zone, any movement triggered by earthquakes is being monitored using a strong-motion accelerograph installed in Taihape Rural Hospital. All the monitoring equipment has been installed as a semi permanent, long-term set up. Data loggers for the piezometers and rain gauges, along with radios and batteries are housed in custom-built cabinets located on 3m high timber poles. The robotic total survey station is housed in a weather-proof hut (Figure 3), with power for all the equipment being generated from photovoltaic cells mounted on poles, or on the roof of the hut. Thus, the system is run remotely without any need for mains power.

3.2 Data transfer, processing and display

The monitoring network operates in a near-real time framework (defined as: the delay introduced, by automated data processing or network transmission, between the occurrence of an event and the use of the processed data), with an approximate end-to-end (site to office) delay of one hour. Wireless transfer of data from the robotic total station, rain gauges, piezometers and strong motion sensor is achieved via radios to the Taihape Town Hall and via the internet to GNS Science buildings located near Wellington (approximately 250km south of Taihape). The data are automatically processed, formatted, checked and made available in both human and machine-readable formats. The results are presented in an intuitive, interactive web-based chart, which is updated at 15-minute intervals and can be viewed via the GeoNet website: www.geonet.org.nz. This allows the data to be viewed easily by the end user. Faults in the equipment and network are monitored using existing GeoNet tools and so the integrities of the equipment and data are also remotely monitored.

4 MOVEMENT PATTERNS OF THE TAIHAPE LANDSLIDE

The approach commonly adopted for the description of the movement patterns of landslides derived from monitoring data concentrates on the analysis of movement velocities and cumulative displacements to try to classify the styles of movement that a landslide displays (Allison and Brunsden, 1990). Taihape is a complex landslide formed of a series of discrete slide-blocks. Movement monitoring of these blocks over the past six months has identified three periods of displacement, the first on 11 to 16 July 2006 (maximum recorded movement rate of 1.6 mm/day); the second starting at the beginning of October and continuing for 6 weeks (maximum recorded rate of 0.07 mm/day); and the third on 8 to 9 November 2006 (maximum recorded rate of 3.5 mm/day).

Analysis of the movement data suggests that the movement patterns within the landslide fall into two distinct types, both in the magnitude of the total displacement and the pattern of movement observed, and are somewhat similar to those patterns observed by Allison and Brunsden (1990) and Petley. et al., (2002).

Type I. Creep – characterised (at Taihape) by slow displacements, with rates typically less than 0.1 mm/day sustained over many weeks and possibly months.

Type 2. Surge – characterised (at Taihape) by more rapid displacements, with rates typically greater than 2 mm/day over short periods of time (days rather than weeks).

The spatial resolution of the movement monitoring equipment has allowed these movement patterns to be correlated with the different slide-blocks forming the landslide, and their location within the overall landslide, with: the toe area of the landslide subjected to Type 1 and 2 displacements (with Type 2 occurring after Type 1); the central area subjected to Type 1 displacements; and no displacement (to date) identified for slide-blocks in the upper part of the landslide. The temporal resolution of the monitoring data has enabled the Type 2 periods of landslide displacement to be linked to the triggering factor. In this case, two periods of prolonged rainfall (cumulative rainfall of 59mm and 65mm peaking on the 11 July and 8 November respectively), which caused increases in the groundwater levels along the slip plane of the landslide (Figure 5). The increase shown by Piezo 1 (figure 5) is most noticeable, with a 2.4m rise in groundwater level recorded prior to the onset of movement. Although type 2 displacements are related to rainfall, Type 1 displacements appear to be unrelated to rainfall and groundwater, and are more likely associated with loss of toe support caused by erosion along the flanks of O'Taihape Valley Stream (Figure 4).

Figure 2: Monitoring reflector (MR facing towards the monitoring hut (MH), containing the robotic total survey station

Figure 3: Monitoring hut and robotic total survey station. Power is derived from solar panels installed on the hut roof

5 CONCLUDING REMARKS

The increased spatial and temporal resolution of the near-real time monitoring network is providing a better understanding of landslide movement patterns. Due to the near-real time monitoring system, periods of movement are now able to be linked to the triggering factors. This gives an improved basis for defining movement triggering thresholds (e.g. rainfall intensity/duration), which when combined with movement thresholds can be used as part of a comprehensive landslide warning system. Data derived from this monitoring network is also providing information required for the design of more effective mitigation measures. Additional work is ongoing to investigate and assess the links between the movement patterns observed at Taihape to changes in material properties and pore-pressure conditions and the inter-relationships between pore pressures and deformation of the materials forming the landslide slip plane.

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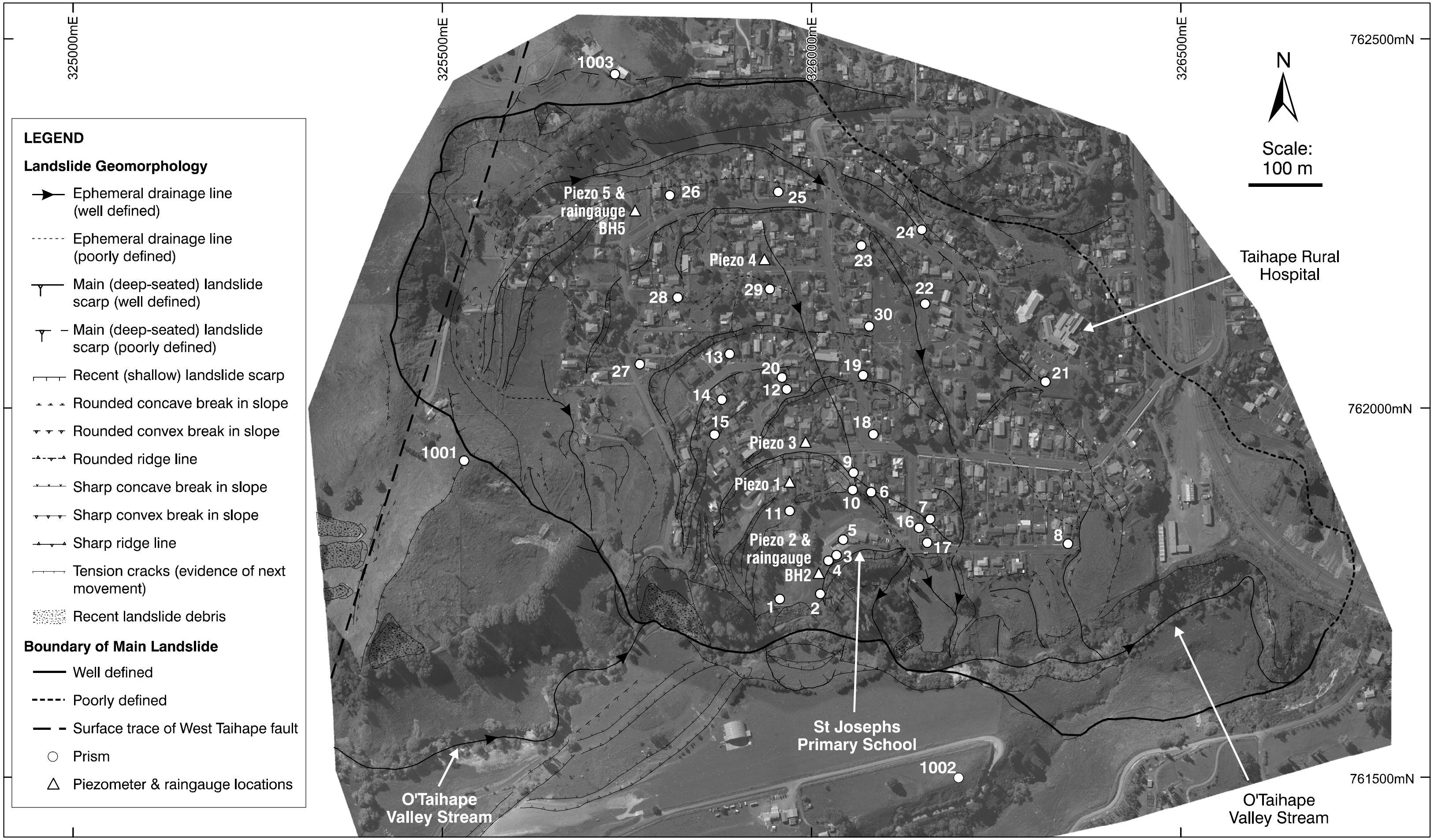

Figure 4: Engineering geology map of the Taihape landslide, showing the location of the monitoring equipment

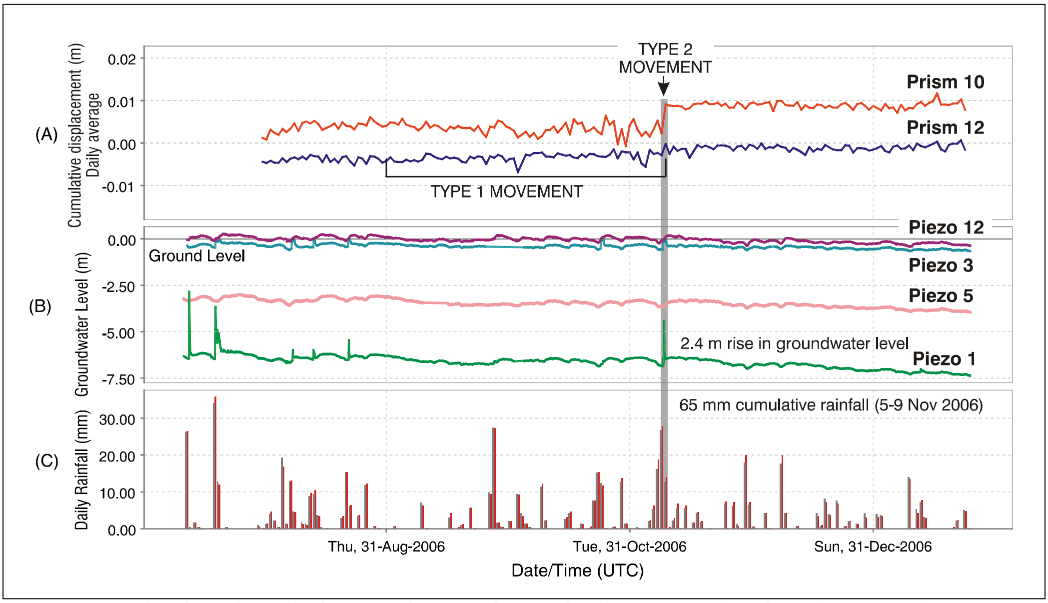

Figure 5: Combined graph showing the cumulative displacements (Graph A) for two reflectors located on the landslide. Movement Types 1 and 2 have been labelled (Graph A) and the rainfall (Graph C) leading to the rise in groundwater level (Graph B), which triggered the Type 2 movement on 8 November.

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